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**FreedomCAR & Vehicle Technologies Program**

# **Plug-In Hybrid Electric Vehicles**

FCVT Activities Contributing to  
the Advanced Energy Initiative

Samuel Taylor, Project Manager  
Power and Vehicle Technology Division  
June 27, 2007





# Topics

- **PHEV mandate/expectations**
  - Advanced Energy Initiative
  - PHEV Discussion Meeting
- R&D Management Plan
  - Overall Plan
  - Near-term focus (Li-Ion, PEEM, Testing)
- Results To Date/Technical Issues
  - Batteries
  - Controls
  - ROI
  - V2G Considerations
- Summary



## **What:**

“A plug-in hybrid electric vehicle (PHEV) is a hybrid vehicle with batteries that can be recharged by connecting a plug to an electrical power source. Plug-in hybrids have characteristics of both conventional hybrid electric vehicles and of battery electric vehicles. While PHEVs are usually passenger vehicles, they can also be commercial passenger vans, utility trucks, school buses, scooters, and military vehicles...”

## **Why:**

“... fuel efficiency ... could exceed 80 or more miles per gallon ... in urban areas...” (for passenger vehicles)

## **How:**

“... charged at night, when electric utilities have spare generating capacity...”

(source: Advanced Energy Initiative)





**Charge Depleting:** Charge-depleting mode allows a fully charged PHEV to operate exclusively (or depending on the vehicle, almost exclusively, except during hard acceleration) on electric power alone until its battery state of charge is depleted to a predetermined level, at which time the vehicle's internal combustion engine or fuel cell will be engaged.

**Charge Sustaining:** Charge-sustaining mode is used by production hybrid vehicles (HEV) today, and combines the operation of the vehicle's two power sources in such a manner that the vehicle is operating as efficiently as possible without allowing the battery state of charge to move beyond some predetermined band.

**All Electric Range (AER):** In a charge depleting mode, the range/period that the vehicle operates on electrical power exclusively.

**PHEV20/40/60:** Typically defined as a PHEV that has # of miles of AER. (I.e. PHEV20 has a 20 mile all electric range)



# PHEV Discussion Meeting

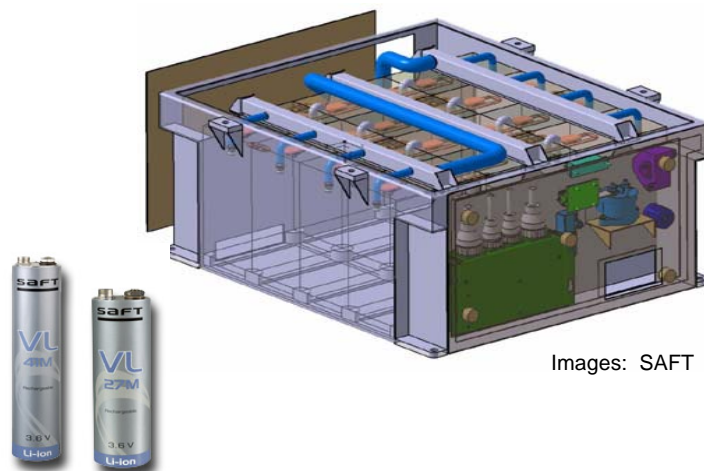
- OFCVT must ascertain whether the national benefits of PHEVs warrant support for R&D to make the vehicles cost-effective and to ensure that the electric power grid can supply the load.
- Meetings held in May '06 and June '07 at DOE with over 120 experts from the automotive and electric utility industries, national labs and academia to discuss PHEV technical and economic issues.





## Executive Summary

PHEVs can substantially improve fuel economy, but cost is the primary impediment and battery technology is a potential show stopper for production.



Images: SAFT



Electric power generation efficiency and the environmental impact of automobiles can be improved by shifting to electricity from gasoline

- off-peak power can handle a large number of PHEVs.



## Executive Summary

- Fuel economy, rather than all-electric range (AER) is the key vehicle metric for the mass market; all other vehicle aspects must be competitive.
- An AER requirement would drive cost up and decrease the likelihood of production.
- Federal government is expected to set policy, support pre-competitive research, act as a trusted source of information and minimize market barriers for PHEVs.





## Recommendations for DOE

- Set policy.
- Support pre-competitive R&D.
- Act as an impartial broker of PHEV information (testing, analysis, codes, standards, etc.).
- Analyze PHEVs technically and economically.
  - Assess the benefits of PHEVs versus alternatives.
  - Quantify the value proposition for automotive manufacturers, electric utilities, consumers and the nation.
- Promote PHEVs if warranted.
  - Remove barriers.
  - Provide incentives.
  - Educate consumers.



## Recap Consensus Points

- PHEVS could displace substantial petroleum.
- **The battery is critical**; electric range and fuel displacement depend on electrical energy storage.
- **All-electric or charge-depleting hybrid-electric range is critical**; all-electric range drives costs up.
- **No critical issues for the electric power grid**
- Further analysis and testing is needed to specify component requirements and quantify PHEV benefits.
- DOE should answer the questions, act as an impartial broker and aid research, development and deployment (if warranted).

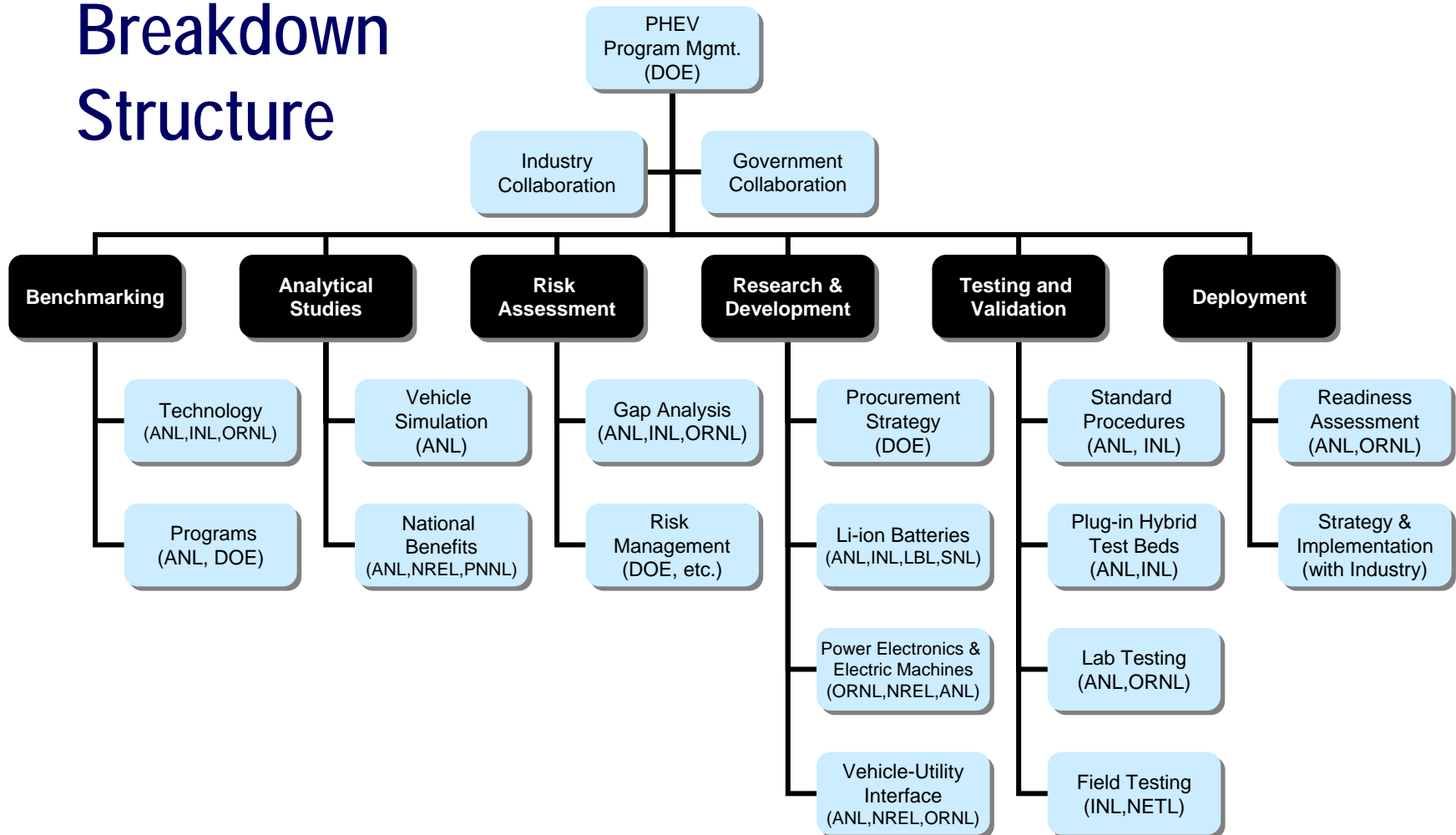


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## Work Breakdown Structure





# Initiated Activities

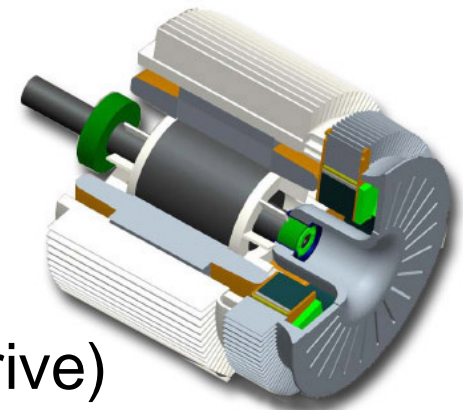
- Programmatic
  - **R&D Management Plan**
  - **Focusing national labs** on answering technical questions and aligning resources
  - **Coordinating** with DOE offices and Federal agencies
- Technical
  - **Solicitations** for Li-ion batteries, power electronics and electric machines (through USABC and NETL)
  - **Analytical studies** to determine optimal battery, power electronics and electric machine requirements
  - **PHEV-specific procedures** for laboratory and field testing
  - **Benchmark testing** Li-ion batteries and PHEV conversions (i.e., preliminary performance characterization)



## Power Electronics and Electric Machines



- PHEV-specific requirements.
  - Power electronics, electric machines, thermal control and integrated systems
- Baseline – 55/30 kW FreedomCAR goal
- Projects Selected in FY07
  - Virginia Tech (High Temp Inverter)
  - Delphi (High Temp Inverter)
  - General Electric (Traction Motor)
  - General Motors (Integrated Traction Drive)
  - US Hybrid Corporation (Advanced DC/DC)





## Li-ion Battery Development

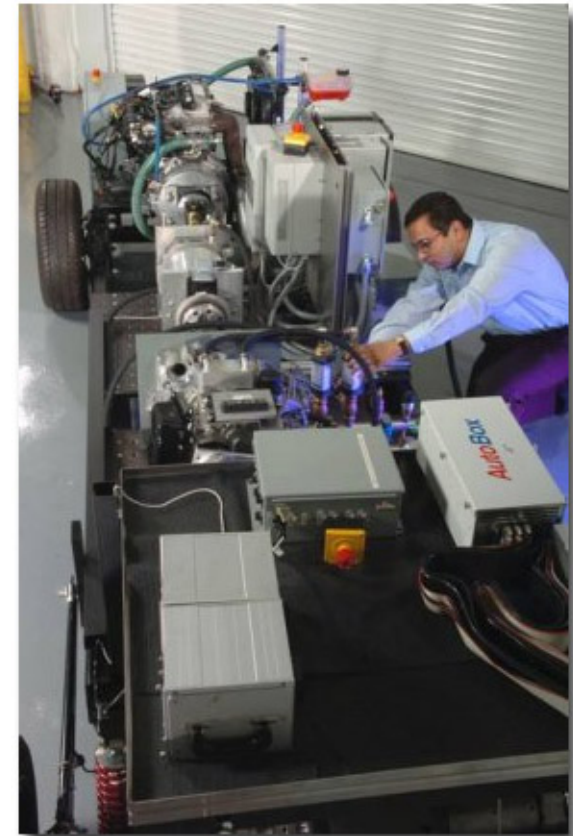
- Draft PHEV-specific requirements.
  - Finalize requirements using vehicle simulation and thermal analysis.
- Develop testing protocols (ANL/INL).
- \$28M Solicitation issued through USABC (closed May 31).
  - Multiple contracts in FY07.
  - Test delivered cells and modules.






## Li-ion Battery Testing

- HIL testing and analysis
  - SAFT-JCI 41Ah battery (10 kWh)
  - Received at ANL in Aug. '06
  - PSAT-PRO virtual vehicle model being prepared
  - HIL bench and dyno testing (using Mobile Advanced Technology Testbed (MATT))
- Bench testing and analysis
  - SAFT-JCI 41Ah battery (10 kWh)
  - Expected receipt by Oct. '06
  - Standard bench testing at ANL/INL
  - Develop battery test protocols for different PHEV drive architectures (AER & CD)
  - Determine battery performance and cycle life for PHEV architectures (AER & CD)



# PHEV Testing

- Vehicle acquisition and instrumentation
    - EnergyCS and Hymotion PHEV conversions
    - Renault Kangoo (rechargeable) HEV
  - Laboratory testing to quantify fuel economy, efficiency and emissions
    - Standard vehicle test procedures TBD (ANL staff chairs SAE J1711 committee).
    - PHEV-specific data acquisition in process.
  - Field testing for on-road performance, economy and operational characteristics
    - Standard procedures TBD
    - Summer testing at INL, balance of year in AZ
- 
- A photograph of a white pickup truck driving on a multi-lane highway. The truck is in the right lane, moving away from the viewer. In the background, there is a metal guardrail and a clear blue sky. The image is partially cut off on the right side.

[illegible]



# Analytical Studies

- Vehicle modeling & simulation
  - Fuel economy potential of PHEVs as a function of propulsion system configuration, component sizing and control algorithms
  - Component performance goals and requirements (for R&D/solicitations)
  - Well-to-wheels energy and emissions analysis (for analysis of national benefits)
- National benefits and impacts
  - Compare PHEVs to hybrids and conventional vehicles, from environmental, cost, design, and marketing perspectives.
  - Electric Utility Impacts
  - National Environmental impacts
  - Synergy with renewable energy sources





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## Plug-In Hybrids

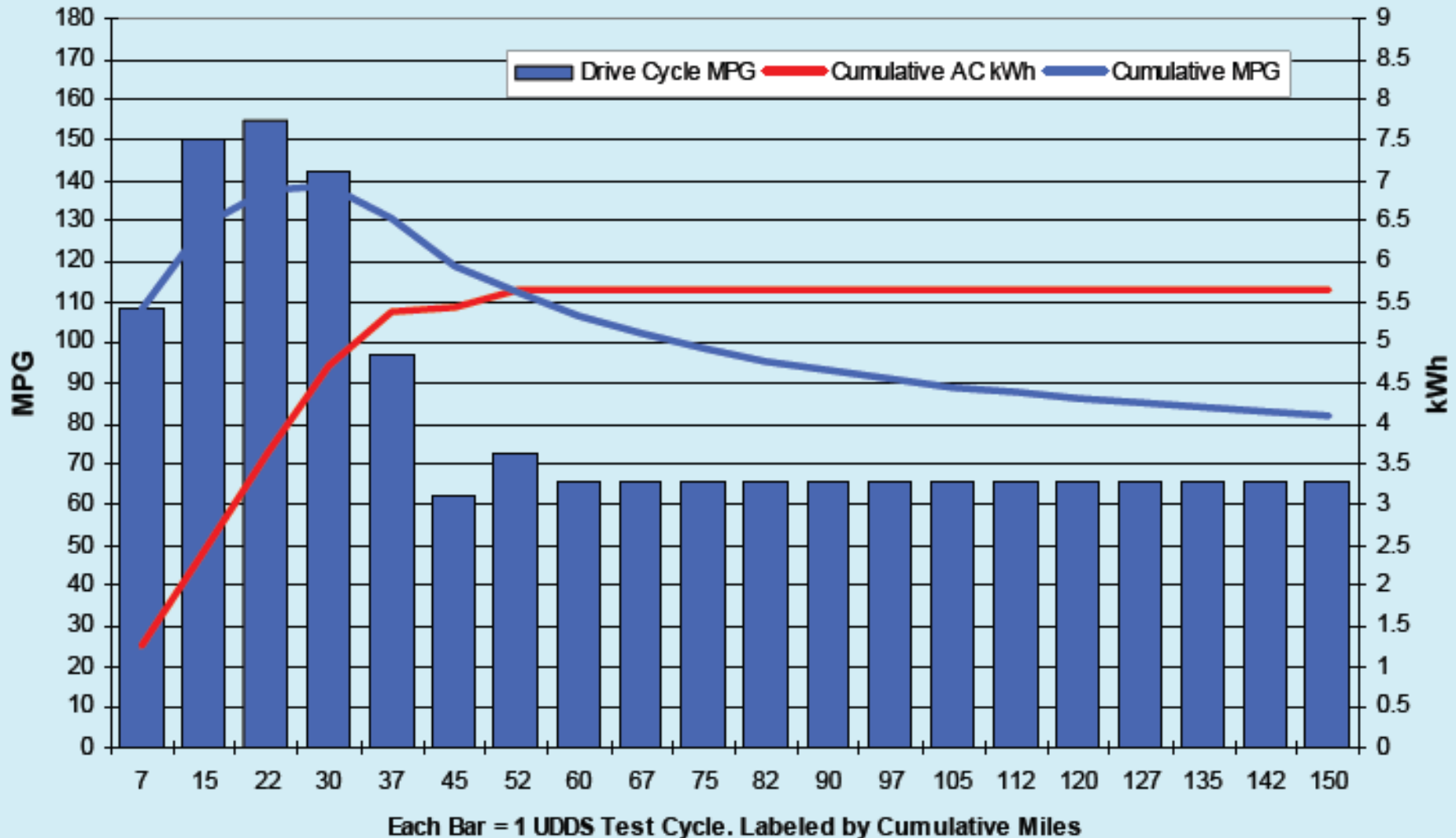
- ❑ **Lithium-ion batteries for PHEVs and EVs are further from commercialization**
  - Improvement in energy density is needed to permit evolution from HEVs to PHEVs.
- ❑ **Critical Barriers include:**
  - Cost of PHEV batteries estimated to be \$1,000 + per kWh
  - Same abuse tolerance issues as HEV batteries, yet with more available energy
  - Volume and weight are issues.
  - Life issues are unknown. Unclear how deep discharges will affect life.
  - Discharge power may be a greater issue at very low temperatures



- ❑ **Cost:** Current estimated cost of lithium-ion batteries for HEVs is about **1.5 to 2 times** the FreedomCAR target.
- ❑ **Abuse Tolerance:** Existing lithium-ion batteries are intolerant to overcharge, crush, and high temperature exposure.
- ❑ **Calendar Life:** Accelerated life testing on multiple lithium-ion electro-chemistries has demonstrated an **8-15 year** calendar life, but getting accurate life prediction is very challenging.
- ❑ **Low Temperature Performance:** Reduction in discharge power is an issue and lithium plating during regenerative braking may reduce life.

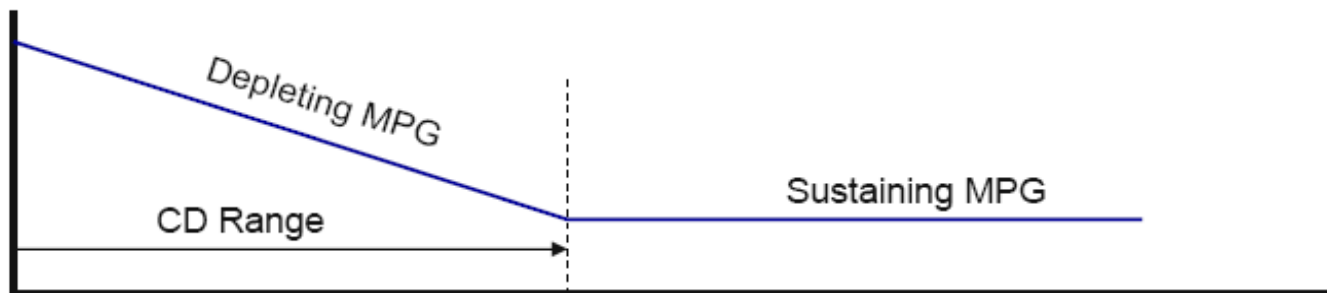


### EnergyCS PHEV Prius MPG & kWh - UDDS Testing





## How Did They Perform? - Full Charge Test Results



UDDS Cycle Charge Depletion Operation	Average Depleting MPG	Ave Battery Usage [Whr/mi]	CD range [miles]	Usable Energy [kWhrs]	Petroleum Displacement Factor [%]	Charge-Sustaining MPG
Kokam Hymotion Prius	178	126	24	2.9	61%	66.4
A123 Hymotion Prius	160	129	25	3.1	60%	64.4
EnergyCS Prius	139	131	34	4.5	55%	62.2

HWY Cycle Charge Depletion Operation	Average Depleting MPG	Ave Battery Usage [Whr/mi]	CD range [miles]	Usable Energy [kWhrs]	Petroleum Displacement Factor [%]	Charge-Sustaining MPG
Kokam Hymotion Prius	122	98	33	3.2	48%	64.0
A123 Hymotion Prius	101	113	31	3.4	46%	55.0
EnergyCS Prius	103	103	50	4.9	44%	58.1



# EnergyCS Prius Accelerated Testing

Cycle (mi)	Urban (10 mi)	HWY (10 mi)	Charge (hr)	Reps (N)	Total (mi)	Actual (mi)	MPG	Miles / kWh
40	2	2	12	5	200	206	144.3	6.87
40	0	4	12	5	200	208	85.5	7.17
60	2	4	12	10	600	621	103.7	10.02
Total	4	10	240	20	1,000	1,035	109.1	8.82
				Gas \$ / Mile		kWh \$ / Mile		Total Fuel \$ / Mile
40	2	2	12	\$0.023		\$0.015		\$0.037
40	0	4	12	\$0.038		\$0.014		\$0.052
60	2	4	12	\$0.031		\$0.010		\$0.041
Weighted Average - (miles)				\$0.031		\$0.012		\$0.043

- Assumes gasoline \$3.25 / gallon & \$0.10 kWh



## PHEV (ECS/HYM) Payback

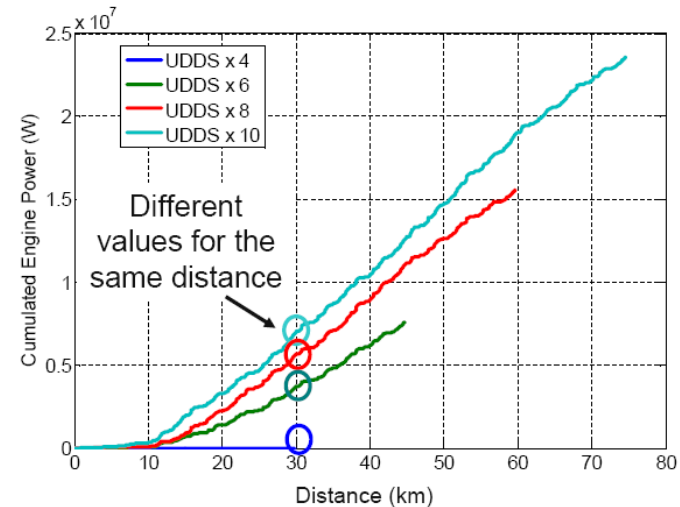
	Miles Driven Per Day	Fuel Savings Per Mile	Conversion Cost	Miles to Payback	Years to Payback
HWFET	40	\$0.021	\$22,500	1,071,429	73
HWFET	60	\$0.021	\$22,500	1,071,429	49
UDDS	40	\$0.033	\$22,500	681,818	47
UDDS	60	\$0.033	\$22,500	681,818	31

- 40 miles / day = 14.6k miles / year. 60 miles / per day = 21.9k miles / year
- PHEV incremental cost = \$22.5k. \$3.25 gasoline & \$0.10 kWh
- **Based on UDDS fuel savings & PHEV DC kWh use**
  - A 100,000-mile, 5-year payback, ~60 miles / day, = \$3,300 battery with 3.1 to 4.7 usable DC kWh
  - Assuming 70% maximum DOD, no life-time capacity loss, = battery with 4.4 to 6.7 DC kWh at \$3,300



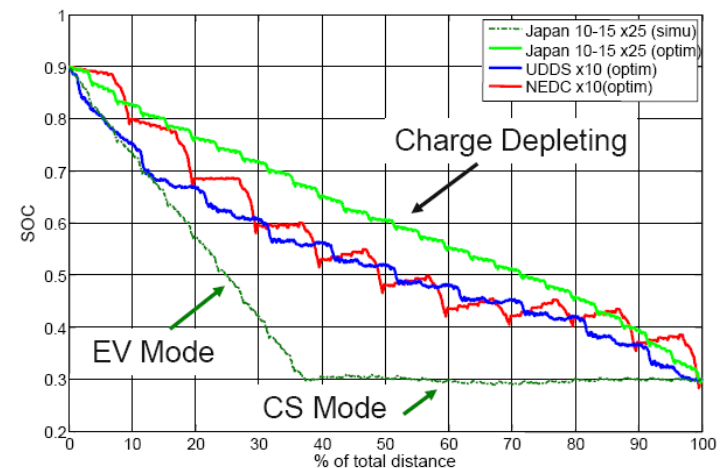
- Controls are a challenge
  - Drive Cycle Dependent
  - Need to operate engine intermittently
- Overall System Efficiency > All Electric Range

### *Optimum Control Depends on Distance*



Global optimization – Pre-transmission parallel midsize HEV

### *Engine Should be Used Throughout the Trip When Distance > AER*



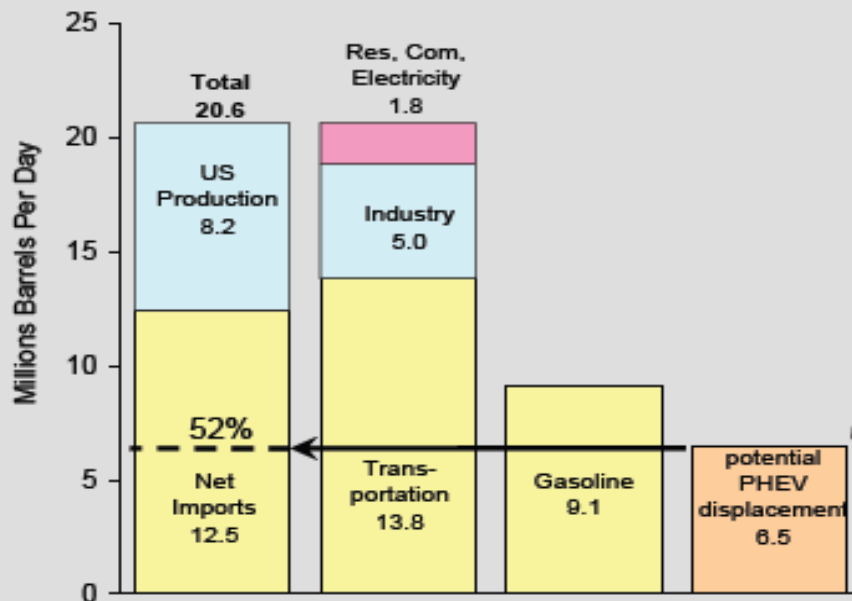
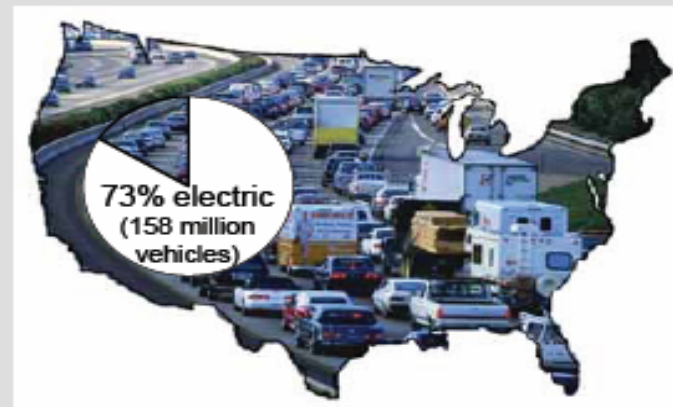
Global optimization – Pre-transmission parallel midsize HEV



## Summary

**The idle capacity of the U.S. grid could supply 73% of the energy needs of today's cars, SUVs, pickup trucks, and vans...**

**without adding generation or transmission if vehicles are charged off peak**



Source: EIA, Annual Energy Review 2005

- ▶ Potential to displace 52% of net oil imports (6.7 MMbpd)
- ▶ More sales + same infrastructure = downward pressure on rates
- ▶ Reduces CO<sub>2</sub> emissions by 27%
- ▶ Emissions move from tailpipes to smokestacks (and base load plants) ... cheaper to clean up
- ▶ Introduces vast electricity storage potential for the grid



# **But, If Charged at Peak Times Electricity May Not be Affordable for PHEVs**

- ▶ Value proposition works for vehicle & utility customers only when off-peak power is used

- off-peak, retail: 7 ¢ /kWh electricity - > \$0.77/gal<sub>e</sub>\*
- on-peak, retail: 33 ¢ /kWh electricity - > \$3.63/gal<sub>e</sub>\*

\* Southern Calif. Edison: TOU-EV1 electric vehicle time-of-use rate

- adding generation, transmission, & distribution to meet new peak loads will drive rates higher not lower

- ▶ Smart charger as an element of a smart grid can:

- communicate price signals to charger
- enforce contract terms for cheap power
- mitigate reliability concerns



# Vehicle To Grid (V2G)

- V2G strategies are still risky
  - Vehicle Manufacturers hesitant to warranty components for use outside of designed application.
  - Impact of V2G on battery life/performance is not well understood
- Large Potential, if technical risks can be overcome



# Regulatory

- Test Cycle for PHEVs is not defined. (Fuel Economy Changes from Cycle-to-Cycle on current tests, AER definition)
- Currently Batteries in HEVs are Emissions Equipment – 80,000mi warranty. Similar requirement for PHEV?
- Safety/Crashworthiness Impacts



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# Summary

- Administrative mandate and ambitious expectations for PHEVs
- Potential benefits warrant more rigorous analysis and focused development of the critical technologies, therefore ...
  - The R&D management plan is being prepared.
  - National lab resources are being focused; facilities and test procedures are being prepared.
  - Component benchmark testing has begun.
  - The solicitation process has been initiated.



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- PHEV components presently add \$15,000-30,000 to marginally cost-competitive HEVs
- PHEV conversions are not capable of full-performance in all-electric mode and do not meet the 40 mile electric range goal
- Battery life and reliability with a PHEV duty cycle are unknown
- **PHEVs must be sold in volume to substantially impact petroleum consumption**



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	FY 2006 Budget Appro. (\$ Millions)			FY 2007 Budget Appro. (\$ Millions)			FY 2008 Budget Request (\$ Millions)		
	HEV	PHEV	Total	HEV	PHEV	Total	HEV	PHEV	Total
<b>Energy Storage R&amp;D</b>	23.1	1.4	24.5	23.5	17.6	41.1	23.6	18.2	41.8
<b>Adv. Power Elec. &amp; Motors</b>	12.9	0	12.9	11.7	2.0	13.7	11.7	3.9	15.6
<b>Vehicle &amp; Sys. Sim. &amp; Testing</b>	8.8	0	8.8	9.7	4.4	14.1	11.7	5.4	17.1
<b>Demonstrations/Utility</b>	0	0	0.0	0.0	4.0	4.0	0.0	0.0	0.0
<b>Total</b>	<b>44.8</b>	<b>1.4</b>	<b>46.2</b>	<b>44.9</b>	<b>28.0</b>	<b>72.9</b>	<b>47.0</b>	<b>27.5</b>	<b>74.5</b>



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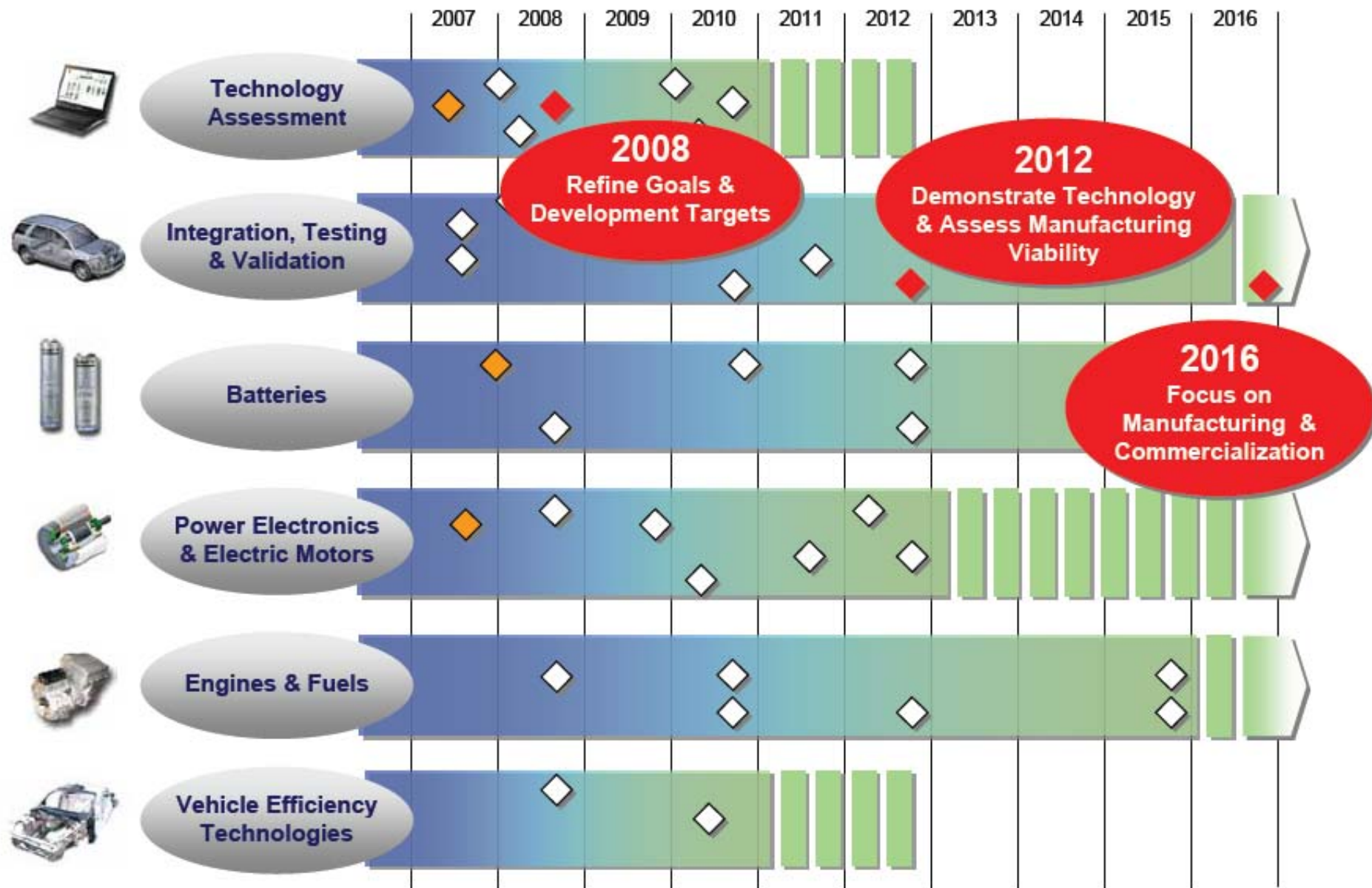
# Questions?



# Backup



# Schedule and Milestones





## **PHEV (ECS/HYM) Payback Assumptions**

- **Average gas & kWh costs - driving 40 & 60 miles / day**
  - **Both PHEVs in UDDS average: ~\$0.039 / mile**
  - **Both PHEVs in HWFET average: ~\$0.051 / mile**
  - **EnergyCS accelerated test: ~\$0.043 / mile**
- **Versus HEV Prius @ 45 mpg: \$0.072**
- **AVTA's PHEVs cost from \$15k to \$40k (\$40k includes data logger). Using \$15 and \$30k (assumes no data logger), average incremental PHEV cost is \$22.5k**
- **Ignores additional battery replacement costs & any additional costs if a vehicle warranty is voided**
- **Payback = PHEV incremental cost compared to lower PHEV fuel cost per mile than HEV fuel cost per mile**



- ❑ **2010 FreedomCAR HEV Goal:** To enable reliable HEVs that are durable and affordable, the goal is:
  - Electric drivetrain energy storage with **15-year life** at **300 Wh**, with discharge power of **25 kW for 18 seconds**, and **\$20/kW**
- ❑ **2014 PHEV Battery Goal:**
  - PHEV energy and power goals (**PHEV-10 and PHEV 40**) have been developed in collaboration with the Vehicles Systems & Analysis Tech Team
  - PHEV cost goal: **\$200-300/kWh**



- ❑ **Lithium-Ion batteries are technically feasible**
  - Synergies between development of HEV and PHEV batteries
  - Batteries specifically built for this application are becoming available for testing
  - Impact of dual mode of operation during charge depleting and charge sustaining on battery life is not understood
- ❑ **Cost is a potential show stopper**
  - Current cost of lithium-ion battery is about \$1000 /kWh
  - The short-term cost goal is \$500/kWh and the long-term goal is \$250/kWh
  - Cost must be reduced without degradation in battery performance
- ❑ **PHEV battery requirements for a variety of vehicle architectures are being developed in collaboration with the Vehicle Systems Tech Team**



## PHEV Testing

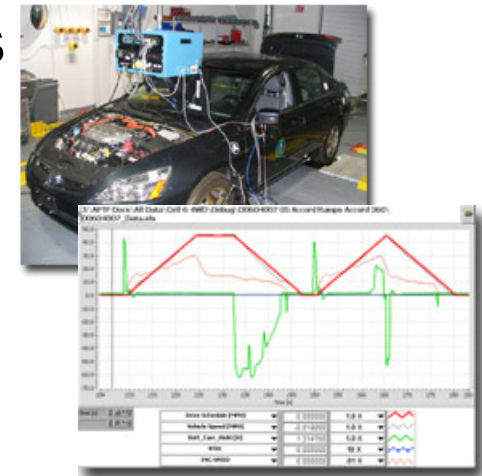
- Benchmark/characterization testing in the laboratory and on-road
- Performance, efficiency, emissions and operational characteristics of conversion vehicles
  - EnergyCS Prius
    - 9 kWh Valence Li-ion pack replaces Ni-MH
  - Hymotion Prius
    - Additional 5 kWh A123 Li-polymer pack
  - Renault Kangoo Elect'road
    - 100 Ah, 132 V SAFT NiCd pack






## Laboratory Testing

- Dynamometer testing with lab-quality instrumentation using standard test procedures and driving cycles.
- Quantify fuel economy, efficiency and emissions under controlled conditions.
- PHEV-specific standard test procedures are being developed (ANL staff chairs SAE J1711 committee).
- PHEV-specific data acquisition system modifications are in process.



# Field Testing

- EnergyCS reprogramming onboard data acquisition system for AVTA
    - Monitor 10 vehicles in fleet applications (7 vehicles currently operating in CA)
  - Study charging practices, energy/power requirements, energy storage issues and costs (INL/ETA)
  - Fleet testing at ETA (Phoenix); summer at INL due to battery operating temperature limits, third location considered
- 
- A photograph of a highway with a guardrail and a clear blue sky. The image is partially visible on the right side of the slide.

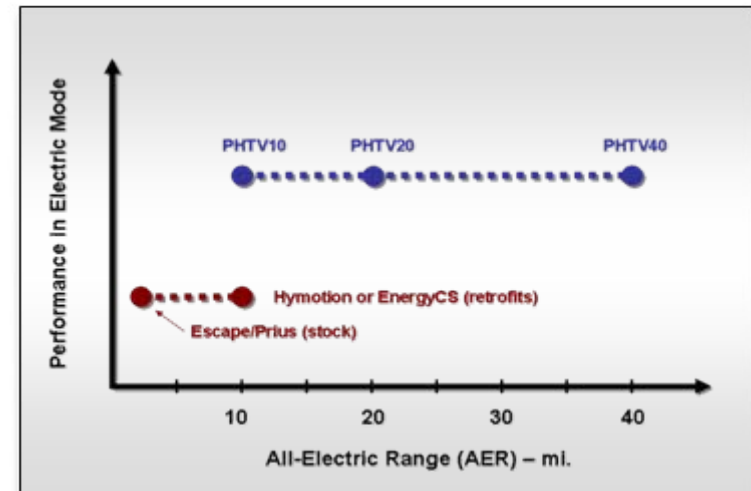




## Plug-In Hybrid Test Beds (PHTBs)



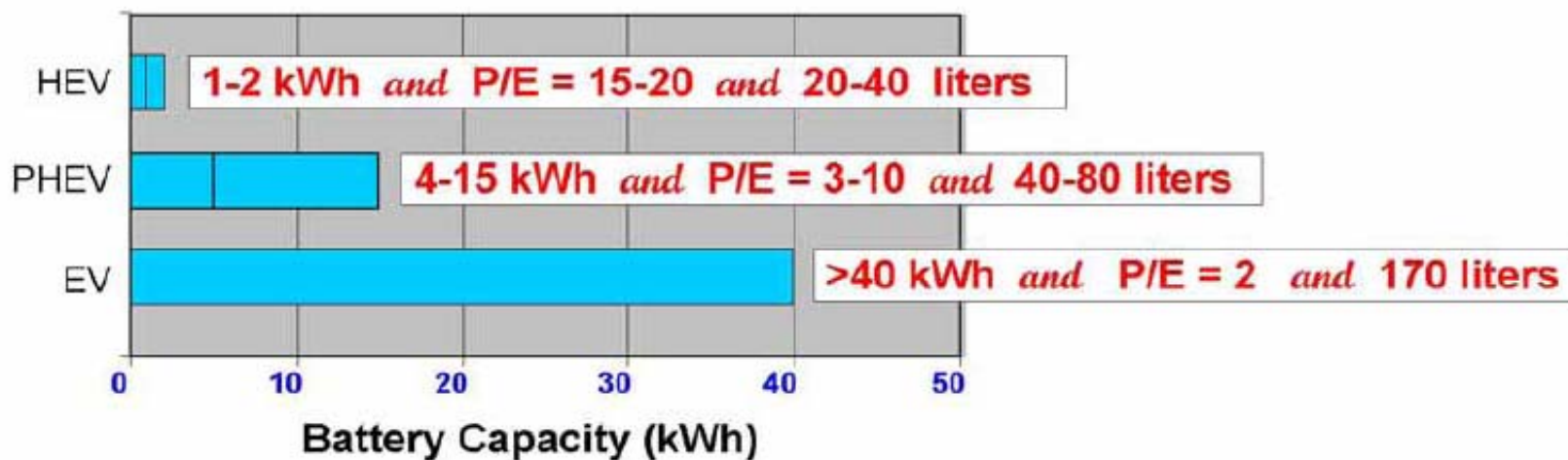
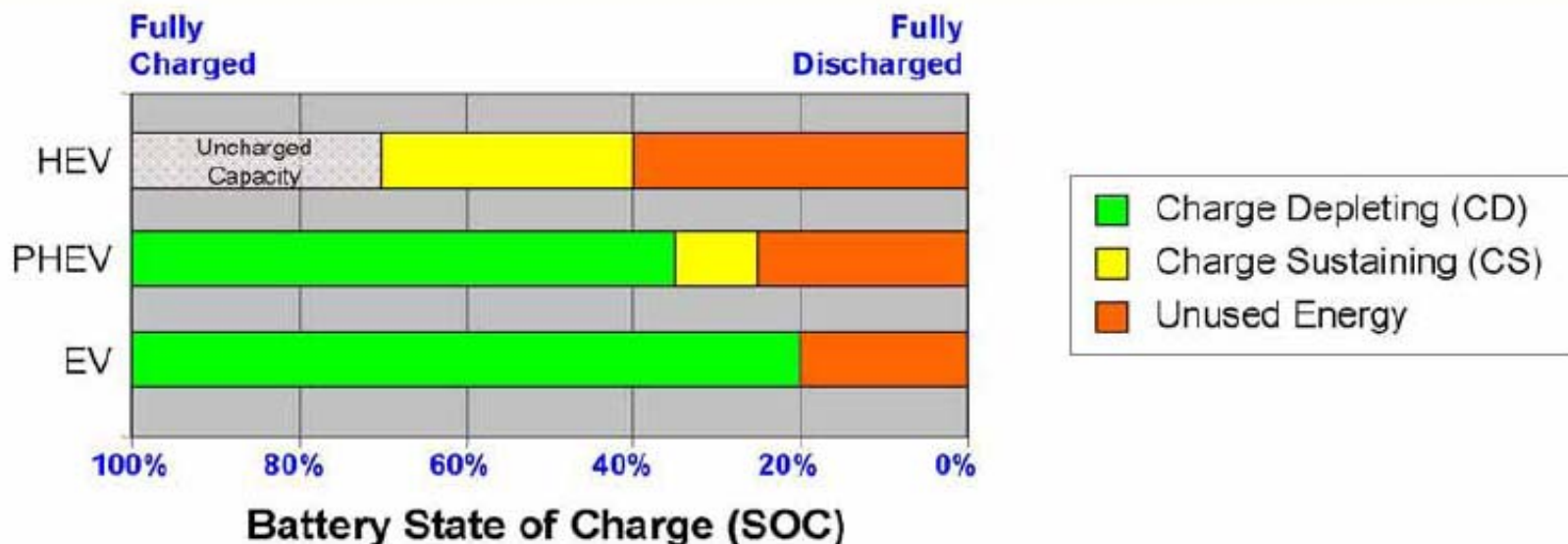
- Full-performance plug-in hybrids
  - **Component performance specs** and control requirements vs. range
  - **Confirmation of test procedures** applicable to charge-sustaining and charge-depleting control strategies
  - **Fuel economy and emissions** vs. electric range and control strategy
- Saturn VUE Greenline Platform
  - Belt-Alternator-Starter (BAS)
  - 2.4 L gasoline engine
  - Augmented to split/RWD full hybrid
  - Augmented to AER hybrid
  - Engine on-off control
  - Lab-quality instrumentation





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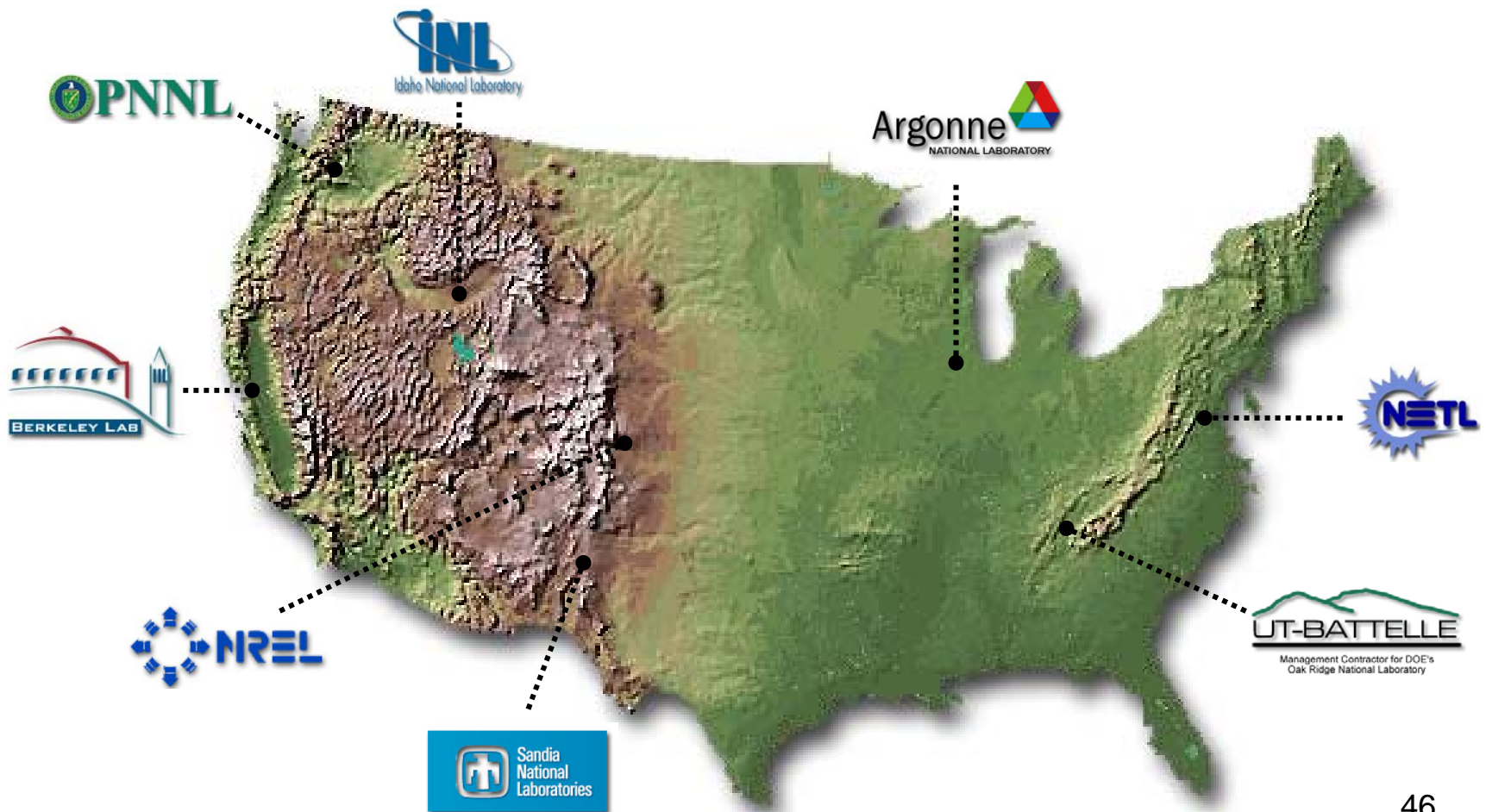


# Smart PHEV Chargers Help Keep the Lights On: Vehicle-to-Grid and Vehicle-to-Home

- ▶ Storage has long been the “Holy Grail” for the grid
  - Batteries in today’s cars (fully charged) could supply the entire U.S. for 20 minutes!
  - Batteries in the analyzed fleet of PHEVs could supply the U.S. for 5 hours!!!
  - Electric vehicles are the highest value use for batteries
- ▶ Smart charger & smart grid can mitigate stress of running grid near capacity
  - Grid Friendly™ chargers can be interrupted when grid is in trouble – “no harm/no foul” – *near term*
  - Vehicle-to-Home: PHEV powers a home in emergencies, take it “off line” when prices are high – *mid term*
  - Vehicle-to-Grid: PHEV feeds power back into the grid, selling reliability services (regulation, spinning reserve) at a profit – *long term?*



## Applicable DOE National Labs





## Facilities/Capabilities



- Advanced Battery Test Facility (ABTF)
- Advanced Lithium Battery R&D Facility
- Advanced Powertrain Research Facility (APRF)



- Advanced Vehicle Testing Activity (AVTA)
- Energy Storage Technology Laboratory (ESTL)



- Advanced Lithium Battery R&D Facility



- Thermal management systems



- Power Electronics & Electric Machinery Res. Ctr. (PEEMRC)
- Fuels, Engines and Emissions Research Center (FEERC)
- High Temperature Materials Laboratory (HTML)



- Exhaust Chemistry and Aerosol Research Center (ECAR)



- Battery Abuse Testing Facility



- ❑ DOE and USABC issued a **\$28 million solicitation** for PHEV battery development on April 5<sup>th</sup>
- ❑ The Purpose of this solicitation was to:
  - Fund battery developers to develop, design, build, and test PHEV battery hardware (cells and modules) which have the potential to meet the USABC PHEV energy storage performance requirements
- ❑ Proposal deadline was May 31<sup>st</sup>
  - 11 proposals received
  - Multiple awards expected during FY 2007